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# An Analysis of the Embodied Energy and Embodied Carbon of Refugee Shelters Worldwide

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*Abstract: The delivery of health, food, and shelter to the 68.5 million people displaced worldwide represents a significant challenge. Camps can house hundreds of thousands of people, and the provision of shelter on such a scale uses considerable amounts of energy and construction materials. Although there have been several attempts to calculate the embodied energy of small numbers of shelters, summary statistics for the embodied energy (EE) and embodied carbon (EC) in general remain unknown. This makes it impossible for those designing shelters to know where their solution sits relative to the median. The primary aim of this article is to resolve this gap by using data collected from eighty-one shelter designs in thirty-four countries to complete the first large scale and global estimate of the EE and EC of shelters. Second, it aims to introduce a web-based and open-access tool, developed to help any stakeholder or interested party obtain an idea of the EE and EC of their design. The median EE was found to be 920 MJ per $m^2$ of footprint with a 95 percent confidence interval (CI) of 599 to 1200 MJ/$m^2$. The median EC was 90 kgCO2e/$m^2$; 95 percent CI [39.2, 99.6]. Importantly, when these figures were further normalised per annum of service life and statistically analysed, more robust shelters did not generally have a greater environmental footprint per annum. Just three material categories—metal, clay bricks/tiles, and concrete—were found to dominate EE and EC.*

*Keywords: Embodied Carbon, Embodied Energy, Refugee Shelters, Shelter Materials*

## Introduction

### *Shelter*

The are an estimated 68.5 million displaced people globally, of which 25.4 million are recognised as refugees, 40 million as internally displaced, and 3.1 million as asylum seekers (UNHCR 2018; UNOCHA 2018). The provision of adequate shelter for this population represents a significant challenge and the volumes of construction materials required present a further resource and environmental challenge (Félix, Branco, and Feio 2013).

This study focuses on shelters for displaced people. These shelters are a crucial solution in natural and human-made post-disaster recovery as they allow the affected population to be sheltered immediately and provide adequate time for aid agencies or involved governments to find durable solutions for the displaced. Given that camps are often the size of cities, the short life cycle associated with temporary housing on this scale can lead to significant environmental impacts (Song, Mithraratne, and Zhang 2016). The need to minimise the environmental impacts of temporary housing has been recognised for some time (Atmaca and Atmaca 2016; Hosseini et al. 2016; Song, Mithraratne, and Zhang 2016).

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The terminology used in the shelter sector varies and is subject to debate (Kuittinen 2015). In some texts, shelters are defined according to the level of permanence (e.g. permanent, transitional, emergency, semi-permanent, and incremental shelter (Quarantelli 1982)). The United Nations High Commissioner for Refugees (UNCHR), in its latest Shelter Design Catalogue (UNHCR 2016), categorised shelters as global, emergency, transitional and durable shelters. This study follows the latter nomenclature:

- **Global Shelter**: This term is used for various shelters such as the UNHCR family tent, UNHCR framed tent, UNHCR self-standing family tent, and the Refugee Housing Unit by IKEA-UNHCR, (UNHCR 2016).
- **Emergency Shelter**: This term is used for designs which vary with location but which, in most cases, are made of a mixture of local materials and UNHCR plastic sheets. They aim to provide immediate adequate living space for new arrivals to the camps.
- **Transitional Shelter**: This term qualifies shelters built for people affected by conflict or natural disasters who have lost or abandoned their housing until they can recover acceptable permanent accommodation. They provide a healthy, secure, and safe covered space, as well as privacy. "Transitional shelter is actually part of an incremental process which starts with the distribution of relief items and continues until durable solutions have been achieved" (Ashbridge et al. 2012).
- **Durable Shelter** (or **Permanent Shelter**): is any form of shelter that normally requires land tenure and obtaining building permits from local authorities.

The service life for global, emergency, transitional and durable shelters according to UNCHR are 1 to 3 years, 1 to 5 years, 2 to 4 years, and 10 years respectively, depending on local climate and level of maintenance according to Shelter Design Catalogue, published by the *Shelter and Settlement Section* of UNHCR (2016). However, in some cases permanent or durable shelters can last up to twenty years—such as the semi-permeant shelters built in Afghanistan, which are made of fire burnt (backed) bricks, dry stone masonry, and/or concrete blocks. In fact, the use of the terms "semi-permanent" or "durable shelter" in such contexts mostly results from political aspects of the projects rather than from technical definitions (Quarantelli 1982).

## *Energy and Carbon*

Studies looking at the environmental impact of existing shelters have been conducted in response to academics, architects, and others showing increasing interest in developing solutions under each of the four shelter categories list above. For example, Escamilla and Habert (2015b) provide a detailed analysis of a small number of pre-existing designs. However, little has been done to support designers in analysing their new designs. Although there are many ways to measure impact, and many forms of environmental impact a shelter might have, increasing concerns over climate change and shrinking availability of natural resources suggest that energy and carbon hold a central place in popular sustainability thinking. In addition, architects and building designers are well used to using energy and carbon as the focus of sustainability due to various regulatory standards across the world. This work attempts to support architects and others by providing a tool for the analysis of their designs and benchmark values for reflection.

Embodied energy (EE) and embodied carbon (EC) are associated with the extraction and transportation of raw materials, and the production of building materials. Academic and industrial research has shown that embodied carbon generally forms a significant part of a building's lifetime carbon footprint and hence interest has grown significantly in the architectural community (Hammond and Jones 2008; Lockie and Berebeck 2014; De Wolf, Pomponi, and Moncaster 2017). The challenge for many building designers when considering embodied energy and carbon—including when designing refugee shelters—is to be able to not only assess quantitatively the embodied energy or carbon of different design options, but also to benchmark and understand whether it has high or low impact relative to other options.

This work tackles the issue of minimising EE and EC by i) providing the first summary statistics on embodied energy and embodied carbon for a large sample of shelters around the world, thereby allowing designers and researchers to be able to discover where their design sits relative to others, and which materials have the greatest environmental impact; ii) presenting a publicly available, web-based tool to carry out these calculations which, alongside providing EE and EC results, shows which materials are the main contributors, and benchmarks each shelter's environmental performance against the values of the eighty-one baseline case studies. Thus, the tool gives a rapid high-level evaluation of the environmental impact of shelter designs and can help to integrate life cycle thinking into the early planning phase of humanitarian responses.

Four normalised units were considered for this research: 1) EE (in megajoules) per meter squared of building footprint; 2) EC (in kilograms of $CO_2$ equivalent) per meter squared of building footprint; 3) EE (in megajoules) per meter squared of building footprint per year of service life; 4) EC (in kilograms of $CO_2$ equivalent) per meter squared of building footprint per year of service life.

### *Life Cycle Assessment*

Life cycle assessment (LCA) is an environmental management tool that quantifies a wide range of environmental impacts associated with a product over its entire life, from production to disposal. LCA has its origins in the fields of "energy analysis" and "resource and environmental profile analysis" in the 1960s and 70s, and was initially codified under the auspices of the Society of Environmental Toxicology and Chemistry (SETAC) in the 1990s (Allen et al. 2008; McManus and Taylor 2015). These formed the basis of the current ISO 14040 series of international LCA standards (ISO 2006a; ISO 2006b). Under the framework of LCA, there is a range of methods that focus on single issues, such as energy resource use or greenhouse gas emissions; the latter often termed the "carbon footprint." At the heart of any embodied energy or carbon assessment of buildings is the need to collate data on the embodied energy or carbon coefficients for each material.

The present study mainly utilises data drawn from the Inventory of Carbon and Energy Database (ICE) which compiles aggregated cradle-to-gate data for over 400 construction materials (Hammond and Jones 2011). The ICE Database was initially devised to be used by various research consortia under the United Kingdom's "Carbon Vision Buildings Programme." This was funded by the Carbon Trust and the Engineering and Physical Sciences Research Council (EPSRC), specifically as part of the Building Market Transformation Project. A public access version was made available on the internet in the late 2000s, and this led to its wide adoption by academics, industries, and governments. For each material selected, the database provides at least one average EE coefficient, describing the total embodied energy per kg of material (based on total primary energy). For most materials, an equivalent EC coefficient (in units of $kgCO_2$-equivalent) is also available. Metals include coefficients for recycled and non-recycled items. For all materials, additional information is also provided about the number of data points from which the average was calculated; the range of those data points; the boundary specification in terms of lowest and highest coefficient found in the literature, and the standard deviation of EE and EC coefficients. Since fuel mix varies, information about the fuel mix and share of each elementary energy type are presented, as well as a graph of the evolution of the fuel mix over time.

The database is a collation of secondary data from sources which may have used a variety of methods with possible variation in the interpretation of cradle-to-gate boundary conditions, which might be difficult to trace. This forms a limitation to ICE openly discussed by Hammond and Jones (2008). The methodology and selection criteria used to produce the database are transparently described in their work and the precision in the result is argued to be relevant when looking at the life-cycle performance of entire buildings. A more robust analysis would require the use of more transparent and consistent data sources such as Ecoinvent, which offers data on a disaggregated unit process level, broken down per technological process (Rebitzer et al. 2004), or environmental product declarations—the latter though being impossible to obtain for local manufacture in the countries where most displacement camps are sited. Such process-level data allows more precision in the results, for example, when evaluating new technologies instead of industry average technologies. However, this requires more precise information about the individual processes used by the industries manufacturing the materials. In the context of this study, such information was unavailable for many countries.

Despite the above-mentioned limitation, the ICE Database was selected in this work for its simplicity of use which allows non-LCA experts to study a diverse range of situations and will, therefore, allow others to easily expand the work to new shelters and new materials. Its use here is further justified by the nature of the study, which considers an entire shelter, and because the EE and EC of a shelter solution can be calculated at an early design stage, at which point the location of the shelter and the source of the construction materials might not be known.

In addition, EE/EC values for many local materials are not known for many of the locations where shelters might be needed (e.g. EE/EC values for brick produced near a refugee camp), thus justifying a cradle-to-gate rather than cradle-to-site analysis. Finally, ICE was also the database used by Kuittinen and Winter (2015), which allowed a comparison between their results and ours, and formed part of our validation.

Alongside ICE, Ecoinvent and the SPINE database (Ecoinvent's Swedish predecessor), there are other publicly funded databases providing life cycle inventory (LCI) data at an aggregated level, such as aggregated resource consumption, wastes, and emissions per kilogram of material produced (Rebitzer et al. 2004) which could be used. Some also compile data obtained using other methodologies, such as the Japanese National database IDEA by Ikaga et al., which is primarily based on an input-output methodology (Curran 2006; Tahara et al. 2010).

### *Previous Work*

There are two notable studies that have looked at the EE/EC values of refugee shelters. Escamilla and Habert (2015b) investigated whether globally or locally sourced materials provide the most sustainable solutions, by carrying out an LCA on twenty shelters designs taken from the International Federation of Red Cross and Red Crescent societies (IFRC) 2012 and IFRC 2013. The IMPACT 2002+ (Jolliet et al. 2003) methodology was used and was focused on a multi-criteria sustainability assessment, not on a narrower EC/EE analysis. The study could not draw any clear correlation between certain material types and a high environmental impact. However, it demonstrated that high cost or environmental impact did not necessarily translate into high technical performance, and that more sustainable solutions can be achieved using both locally or globally sourced materials. It also concluded that local materials generally resulted in a lower cost and environmental impact, but global materials provided better technical performance. A clear difference between this work and ours is that Escamilla and Habert were interested in studying shelters *in-situ* and therefore included transport emissions. The current study, however, focuses on shelter design in general, hence providing an analysis prior to knowing the location of deployment.

The second study (Kuittinen and Winter 2015) investigated the EE and EC of eight shelters and the importance of LCA thinking in the humanitarian context. They used energy and carbon coefficients taken from the ICE Database (Hammond and Jones 2011) to study EC values for two scenarios: assuming wood is taken from a sustainably managed forest (carbon storage subtracted from EC) and assuming it is not (carbon storage maintained). This was done by calculating the overall EE and EC values in terms of i) MJ and $kgCO_2e$ per $m^2$ and ii) MJ per year of service life and $kgCO_2e$ per year of service life, thereby exploring the possible correlation between environmental impact and durability/longevity of the shelter. No correlation was found, which could relate to the small sample size. Additionally, the dissociation of the normalised unit into either size or longevity, rather than both, makes it impossible to consider both factors simultaneously.

## Method

For each of the eighty-one shelters, the boundary conditions for embodied energy and carbon estimates were cradle-to-gate, which are the boundary conditions of the ICE Database data. Cradle-to-gate boundaries include the energy and carbon associated with raw material extraction, transportation to manufacturing plants, and manufacturing and fabrication into building materials. They exclude: i) energy and carbon associated with transportation to the construction site (as this study considers that the location is not yet known); ii) the construction process itself; iii) the operation of the finished building (which is climate, and thus also location dependent); and iv) the end of life (e.g. disposal) stage (as again this involves location-dependent figures, often unknown in a humanitarian context). The material inventory was developed using seven documents from three sources (UNHCR, Shelter Cluster and Danish Refugee Council). Table 4 in Appendix 1 presents these documents, the shelters selected, and the labels used to identify them in this paper. The shelters were selected by prioritizing the documents that provided detailed bills of quantities. It should be stressed that our analysis and interest is not on commenting on the EE or EC of particular designs, but in looking at the summary statistics of the whole sample.

For a few shelters, lists of materials were inferred from pictures and details mentioned in the narratives provided in the seven documents. In these cases, volumes were estimated and standard densities applied to generate weights as required for use with the ICE Database (Hammond and Jones 2011). The lack of knowledge about the timber species used in different projects is a cause of uncertainty in the results because of the high variability of densities between species. For example, species of hardwood can range from 90kg/m$^3$ to 800kg/m$^3$ (Hammond and Jones 2011). Many designs of transitional shelters use locally sourced hardwoods which vary depending on the country of implementation. When unspecified, timber density was assumed conservatively as the density of softwood (510 kg/m$^3$) which is somewhat greater than the median value of the above-mentioned range.

It is common practice in the timber industry to use offcuts from wood production as a biomass energy source to be utilized during the timber production process. Therefore, the ICE Database presents carbon coefficients in two parts: one coefficient representing the fossil fuel energy share and another representing the biomass energy share. Each coefficient is of a similar order of magnitude. When sourced from a sustainably managed forest, the biomass share can be considered carbon neutral and therefore not included (Hammond and Jones 2008). Hence, wood from unsustainably managed forests represents as significant increase in environmental impact (around twice the impact of wood from a sustainable source). In this study and following common practice, timber is assumed to be sourced from a sustainably managed forest, and therefore only the ICE coefficient associated to fossil fuels was used.

Carbon sequestration during the growing of trees and biogenic carbon storage within bio-based and timber building products is a complex area of carbon foot printing (Hammond and Jones 2011). If included in an embodied carbon study, it can lead to net negative carbon values for timber products (i.e. they are considered to create a net carbon saving). However, such a benefit depends on what happens to the timber at the end of a building's lifetime. For example, if bio-based products are put into landfill their decomposition produces both carbon dioxide and methane (Lockie and Berebecki 2014), the latter being a particularly powerful greenhouse gas. The present study focuses on cradle-to-gate impacts and its scope does not include the end of life phase of the shelters, in accordance with modern guidance. Given this, to be conservative, (Lockie and Berebecki 2014), biogenic carbon storage benefits were excluded from this study. (For a more detailed discussion of biogenic storage, the reader is pointed to Levasseur et al. 2012; Levasseur et al. 2013; Tellnes et al., 2017; Vogtländer, Velden, and Lugt 2014). Coefficients for bamboo were not available in the ICE database. Hence values were taken from Escamilla and Habert (2015b). For plastic materials, coefficients excluding feedstock energy were selected (i.e. the calorific value of the raw material is ignored).

Identifying coefficients for poly-cotton fabric, which is the main material in the UNHCR tent designs, required a review of the current LCA literature as they were not available in the ICE database. No specific studies could be found presenting data for a poly-cotton fabric (40 percent cotton-60 percent polyester), so data for polyester and cotton were obtained separately and combined based on the most suitable data found by Velden, Patel, and Vogtländer (2014). This work carried out LCA benchmarking of various textiles including polyester and cotton. It concluded that the footprint of a fabric depends largely on the density of the weaving and thickness of the yarn measured in units of Decitex (dTex) and provides EE and EC coefficients for cotton and polyester fabrics for different dTex values (Velden, Patel, and Vogtländer 2014). The UNHCR documentation used in the present study for the bill of materials does not specify the yarn thickness of the poly-cotton fabric and attempts to deduce the yarn thickness from the specific density were unsuccessful. As a result, coefficients for the thinnest yarn thickness were selected as a conservative assumption (as the study by Velden, Patel, and Vogtländer 2014 gave these the highest per unit weight EC and EE values), and combined in a 40:60, cotton: polyester ratio to represent the poly-cotton fabric in question.

### *Validation*

Validation of a subset of results was carried out through comparison of the eight results for shelters from document 2 in Table 4 of Appendix 1 to the results reported in Kuittinen and Winter (2015) which assessed the same eight shelters. A comparison of the results is given in Figure 1 and Figure 2. Within the precision of EE and EC studies, the comparison seems reasonable, with the discrepancies arising most probably from the exact definition of some materials.

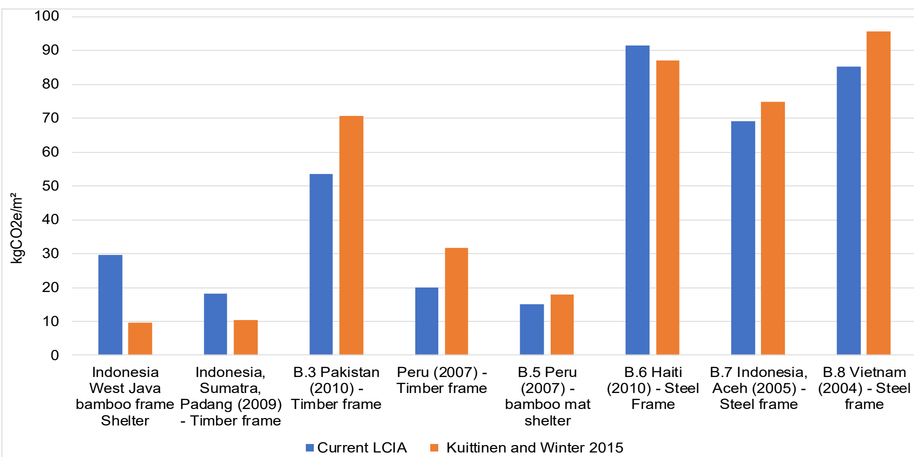


Figure 1: Comparison $EC_1$ Values from Our Online Tool and the Results Reported in the Study by Kuittinen and Winter 2015
*Source: Matard 2019*

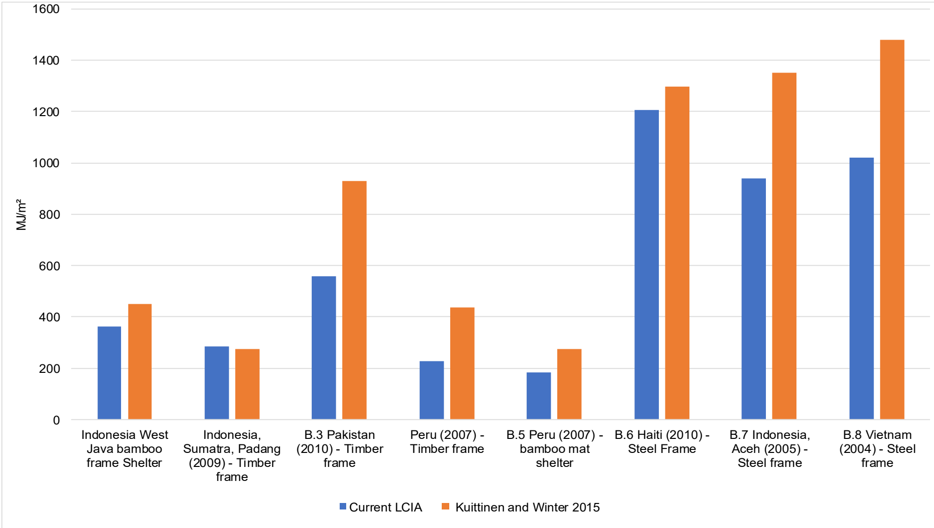


Figure 2: Comparison $EE_1$ Values from our Online Tool and the Results Reported in the Study by Kuittinen and Winter 2015
*Source: Matard 2019*

### *Key Equations*

The embodied energy $EE_1$, embodied carbon $EC_1$, lifetime weighted embodied energy $EE_2$ and lifetime weighted embodied carbon $EC_2$ were calculated using:

$$EE_1 = \frac{1}{A}\sum_i E_i m_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$EC_1 = \frac{1}{A}\sum_i C_i m_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$EE_2 = \frac{1}{A \times L}\sum_i E_i m_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$EC_2 = \frac{1}{A \times L}\sum_i C_i m_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where A is the building footprint ($m^2$), $E_i$ is the embodied energy coefficient (MJ/kg) (from the ICE database) for each material i, $C_i$ is the embodied carbon coefficient ($kgCO_{2e}$/kg) (from the ICE database) for each material, $m_i$ is the mass (kg) of each material, and L is the design's service life (in years). Service life is defined as the time period for which a structure performs its function without unforeseen or extraordinary maintenance or repair (Aurich, Fuchs, and Wagenknecht 2006). In this study, the service life is obtained from either source documents or visual inspection (see "The Impact of Service Life" section and Table 2).

## Results and Discussion

### *Summary Statistics*

Table 1 gives the summary statistics—the mean (and median) embodied energy is 1130 (920) MJ per m² building footprint ($EE_1$), or in carbon units ($EC_1$), 120 (90) $kgCO_{2e}$ per m². Individual EE and EC values calculated for the eighty-one shelters can be found in Table 5 in Appendix 2.

Table 1: Descriptive Statistics for the 81 Shelters

| Characteristics | EE1 (MJ/m$^2$) | EC1 (kgCO2e/m$^2$) | EE2 (MJ/m$^2$/year) | EC2 (kgCO2e/m$^2$/year) |
|---|---|---|---|---|
| Mean | 1130 | 120 | 240 | 23.6 |
| Median | 920 | 90 | 155 | 12.9 |
| Standard Deviation | 1080 | 148 | 216 | 27.7 |
| Minimum | 36.0 | 2.11 | 12.2 | 0.843 |
| Maximum | 6000 | 840 | 1200 | 137 |

*Source: Matard 2019*

The results also show a large variation: 36 MJ/m² to 6000 MJ/m² for $EE_1$; 2 $kgCO_2e/m^2$ to 840 $kgCO_{2e}/m^2$ for $EC_1$. Evaluating the magnitude of the variation reflected by the standard deviations (1080 MJ/m² for $EE_1$ and 148 $kgCO_{2e}/m^2$ for $EC_1$) is difficult given the lack of previous data set against which it could be benchmarked for comparison. However, noting that the values of the means of $EE_1$ and $EC_2$ are of similar magnitude to their respective standard deviations suggests that the dataset is significantly dispersed around the mean with a few largely outlying values.

Plotting the $EE_1$ results as a histogram (Figure 3) shows that the results are far from normally distributed. A similar trend would be seen in an equivalent $EC_1$ graph. Figure 3 shows a skewness of the tail to the right, with most shelters having relatively low EE per m$^2$ and a small number of outliers having the highest values. For example, approximately 80 percent of the shelters have $EE_1$ estimates below one quarter of the maximum $EE_1$, suggesting that the use of percentiles when benchmarking future shelter designs will be more useful than the mean and range, and Table 2 gives the quartile boundaries to allow this.

Table 2: Quartile Boundaries

| Quartile Boundaries | $EE_1$ (MJ/m²) | $EC_1$ ($kgCO_2e/m^2$) | $EE_2$ (MJ/m²/yr) | $EC_2$ ($kgCO_2e/m^2$/yr) |
|---|---|---|---|---|
| Minimum | 36.0 | 2.11 | 12.2 | 0.843 |
| $Q_1$ | 363 | 19.3 | 86.7 | 6.77 |
| $Q_2$ (median) | 920 | 90.0 | 155 | 12.9 |
| $Q_3$ | 1497 | 138 | 315 | 30.8 |
| Maximum | 6000 | 840 | 1206 | 137 |

*Source: Matard 2019*

The distribution is reasonably well represented by a median $EE_1$ of 920 MJ/m$^2$ with a 95 percent confidence interval (Campbell and Gardner 1988; Gardner and Altman, 1986) of 599 to 1200 MJ/m$^2$. For $EC_1$, the equivalent results are a median of 90 kg$CO_{2e}$/m$^2$ with a 95 percent confidence interval of 39.2 kg$CO_{2e}$/m$^2$ to 99.6 kg$CO_{2e}$/m$^2$.

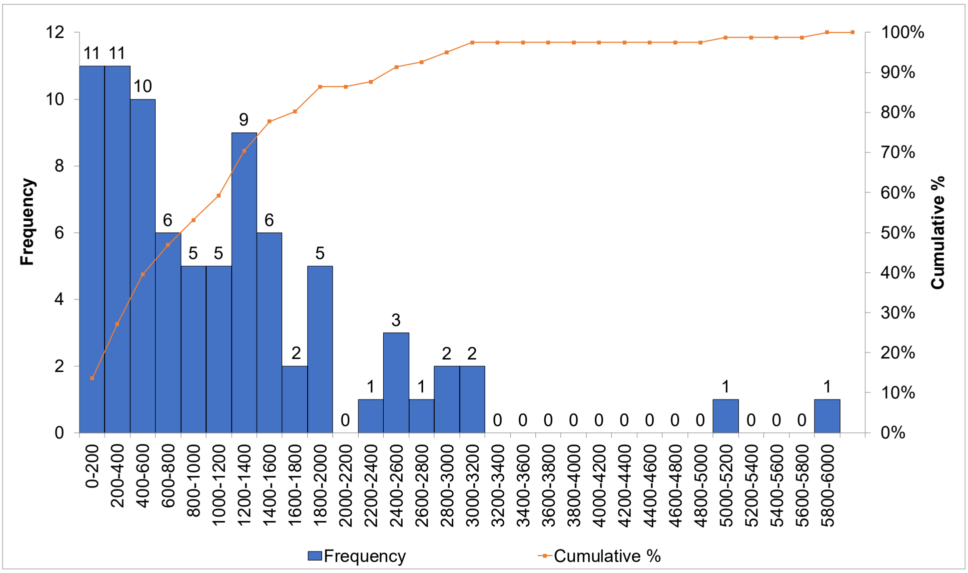


Figure 3: Distribution of $EE_1$ for 81 Shelters
*Source: Matard 2019*

## *Key Materials*

Figure 4 shows the breakdown of the embodied energy per m$^2$ by material for each shelter design, and Figure 5 shows the breakdown for embodied carbon per m$^2$ of each shelter studied. Durable shelters have a code beginning with “D,” transitional shelters begin with “T,” emergency shelters with “E,” and global shelters with “G.” Note that stones and aggregates are treated separately: aggregates are used for making concrete or foundation fill, and stones are masonry units.

Two observations may be made. First, durable shelter designs tend to have the highest $EE_1$ and $EC_1$, with transitional, emergency, and global shelters having lower results. Second, the key materials dominating embodied energy and carbon tend to be metal, clay bricks/tiles, and concrete. Timber is also important for some designs when biogenic carbon storage benefits are ignored (as discussed earlier). For 78 percent of shelters in the sample, a single material is responsible for more than half of the shelter’s $EE_1$. For 68 percent of shelters in the sample, a single material is responsible for more than half the $EC_1$. Some caution is needed here, as has been emphasised at several points, this analysis is being completed for those looking at early-stage design, so without knowledge of the location of the shelter, nor knowledge of the location of the production of the materials.

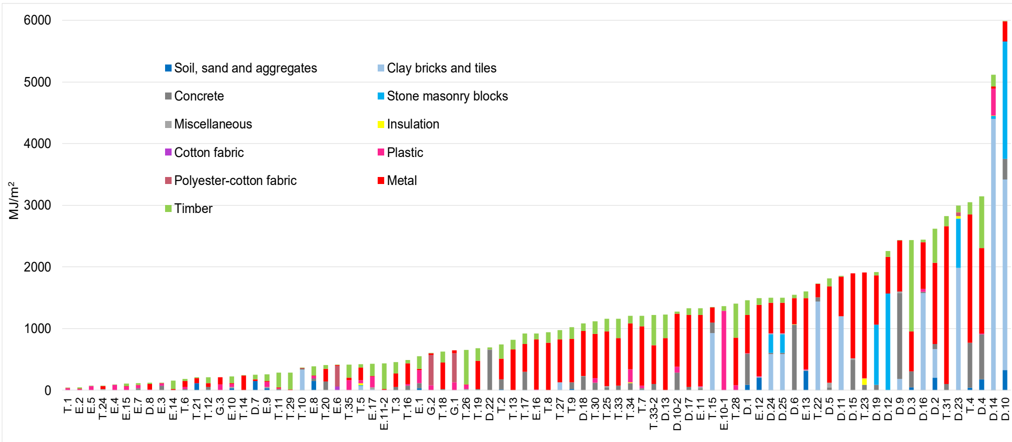


Figure 4: Breakdown of Embodied Energy per m$^2$ ($EE_1$) for Each Shelter, by Construction Material
*Source: Matard 2019*

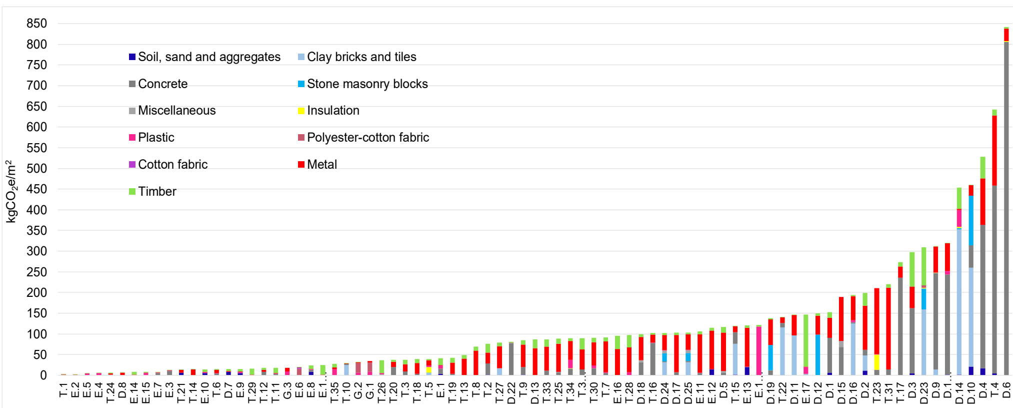


Figure 5: Breakdown of Embodied Carbon per m$^2$ ($EC_1$) for Each Shelter, by Construction Materials
*Source: Matard 2019*

Summing across all eighty-one shelter designs, Figure 6, Figure 7, and Figure 8 show which materials dominate total $EE_1$, $EC_1$, and mass, respectively. Looking at Figure 6 and Figure 7, we see that in terms of total $EE_1$ across all designs, metal is responsible for the highest fraction, followed by clay bricks/tiles and concrete; these three material categories together represent 72 percent of the total $EE_1$. For $EC_1$, concrete is the biggest contributor followed by metal and clay bricks/tiles, which taken together represent 79 percent of total $EC_1$. By also considering Figure 8, we can see that metal is particularly energy and carbon intensive per kg used, representing just 4 percent of mass but 43 percent of $EE_1$ and 31 percent of $EC_1$.

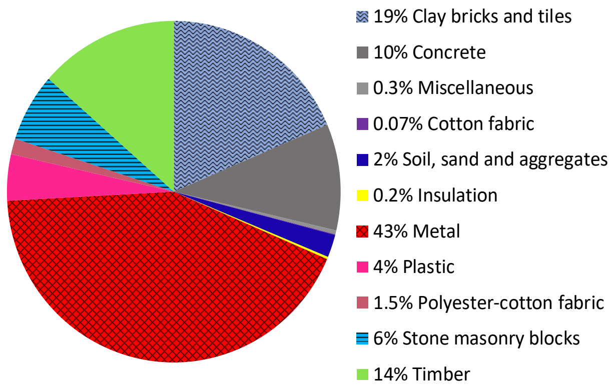


Figure 6: Material Fraction in All Cases Studied for $EE_1$
*Source: Matard 2019*

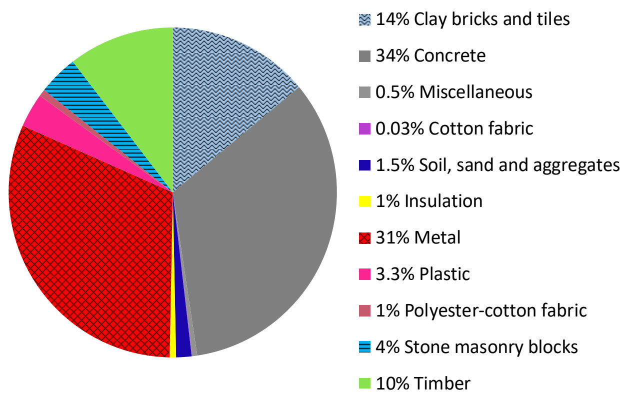


Figure 7: Material Fraction in All Cases Studied for $EC_1$
*Source: Matard 2019*

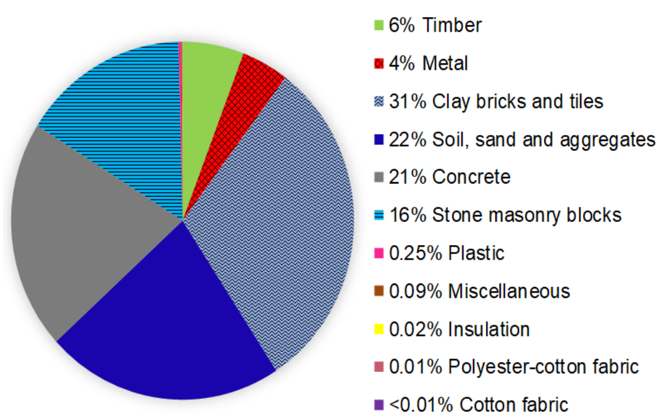


Figure 8: Material Mass per $m^2$ Across 81 Designs Studied
*Source: Matard 2019*

Whilst Figure 6, Figure 7, and Figure 8 aid interpretation of the key materials across the eighty-one designs, they sum the results from each shelter design and do not consider the prevalence of each design on the ground. For example, polyester-cotton fabrics were found to be energy and carbon intensive materials, but they only feature in three of the eighty-one designs analysed, hence appearing as a minor share in Figure 6, Figure 7, and Figure 8. In fact, those three designs are "global shelter" designs that are a common solution in humanitarian responses. Poly-cotton fabrics may, therefore, be a more important material in practice than the summary figures suggest.

Figure 4, Figure 5, Figure 6, and Figure 7 together illustrate the importance of metals in $EE_1$ and $EC_1$. The coefficients in the ICE Database suggest that increasing the recycled content of metals such as steel and aluminium—the main metals used in shelter construction—can more than halve the EE and EC of the metals (Hammond and Jones 2011). Important reductions in embodied energy and embodied carbon might, therefore, be achieved by increasing the recycled content of the metals used in shelter design.

Looking at the results, it is apparent that one or more of the following three strategies will, wherever practicable and depending on the design, be important for minimising embodied energy and carbon during early-stage design work: 1) increasing material efficiency (reducing the volume of material used), particularly for the key material categories identified above; 2) material switching from higher to lower EE/EC materials; 3) increasing the use of recycled materials.

### *The Impact of Service Life*

In the above analysis, the service life of the shelter has been ignored. $EE_2$ and $EC_2$ include service life in the normalisation, and as earlier indicated by Table 1. The median $EE_2$ is 155 MJ/m$^2$yr, with 95 percent CI [135, 204] and the median $EC_2$ to 12.9 kgCO$_{2e}$/m$^2$yr, 95 percent CI [9.95, 18.9].

Figure 9 gives the breakdown of the embodied energy per m$^2$ per year ($EE_2$) by material for each shelter design; Figure 10 gives $EC_2$. Durable shelters are now distributed throughout the results, suggesting that on a per-year-of-life basis, the more robust shelters may not in all instances have a greater footprint.

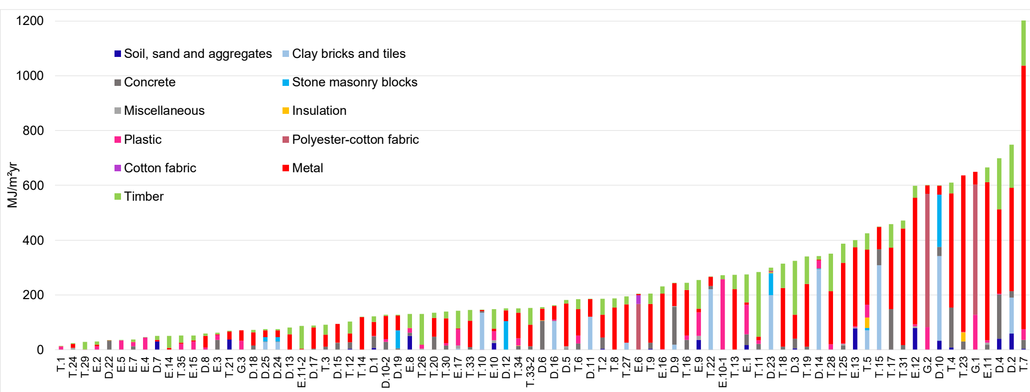

Figure 9: Breakdown of Embodied Energy per m2 per Year (EE2) for Each Shelter, by Construction Material
*Source: Matard 2019*

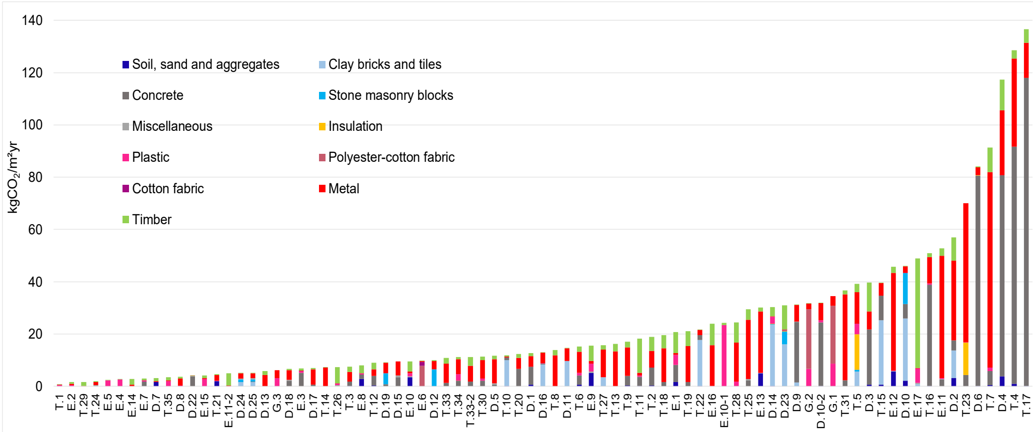


Figure 10: Breakdown of Embodied Carbon per m$^2$ per Year ($EC_2$) for Each Shelter, by Construction Material
*Source: Matard 2019*

The range of service lives together with the number of each shelter category is summarised in Table 3. While Table 4 in Appendix 1 provides information regarding the specific design/service life of each shelter design which was used in the calculation of $EE_2$ and $EC_2$. It is worth noting that in most cases the shelter designs had a published service life range, and the actual operational life will vary in practice due to climate or maintenance issues. Service life was obtained in the following way: 1) if the source document gave a service life, this value was used; 2) if no service life was given, but the shelter was classified as Global, Emergency, or Transitional, the mean of the service life range for this category was used (The mean of the service life was obtained from the Shelter Design Cataloged (2016)). However, SDC provides service life for only two types of durable shelters while various design types of durable shelters with longer service-life have been evidenced in other relevant publications; (3) if no service life was given, and the shelter was not classified as a particular type, visual inspection was used to classify it (as Global, Emergency, Transitional, or Durable) and once more, the mean of the service life given for this shelter type in SDC was used, with the exception of Durable shelters, where in most cases visual inspection was used to estimate the service life.

Table 3: Shelters per Category and Their Assumed Service Lives

| Shelter Type | Global Shelter | Emergency Shelter | Transitional Shelter | Durable Shelter |
|---|---|---|---|---|
| Number of shelter designs studied | 3 | 17 | 36 | 25 |
| Service life (years) given in SDC | 1–3 | 1–4 | 2–4 | 10+ |
| Assumed service life (years), mean of SDC values above | 1.5 | 2 | 3 | n/a |
| Number of shelters where service life is given in source documentation | 3 | 18 | 26 | 5 |
| Number of shelters where service life was not given in source documentation | 0 | 0 | 9 | 20 |

*Source: Matard 2019*

Figure 11 provides box plots that summarise the EE and EC per year of the service life of all shelter designs. Comparing the inner quartiles of $EE_1$ and $EC_1$ (i.e. ignoring service life) with $EE_2$ and $EC_2$ (normalising by service life), it can be seen that the more durable shelter types usually result in a higher range of embodied energy and carbon values (and a higher median) compared to other shelter types when the service life is not considered, but broadly similar ranges are displayed across the shelter types when service life is considered.

Since the data is non-parametric, the Spearman rank is best used to test the correlation between service life and the embodied carbon of the shelters. The Spearman rank correlation coefficient (r) was found to be 0.571. Testing the null hypothesis, of no association between $EC_1$ and the life span of the shelters, against the two-sided alternative, by calculating the test statistic (found below) and comparing against a t-distribution with 81 – 2 = 79 degrees of freedom; the associated p-value (probability of happening) is $2.62 \times 10^{-8}$. This gives us strong evidence to reject the null hypothesis and suggests that there is a moderate correlation between service life and embodied carbon of the shelter.

$$r\sqrt{\frac{n-2}{1-r^2}}$$

The value of the test statistic is as follows:

$$0.571\sqrt{\frac{81-2}{1-(0.571)^2}} = 6.18$$

It is worth noting that the service life of some shelters considered in this research is uncertain. Examples are the shelters in Afghanistan (D.25), the cobblestone walls and wooden bracing shelter (D.19), and concrete block-based shelters (D.15). The majority of the prefabricated (off-site constructed) shelters have a specific service life, which is provided by the relevant manufacturing companies, but the service life for self-built shelters which are made of local materials in most cases is uncertain and not provided by the implementing agency.

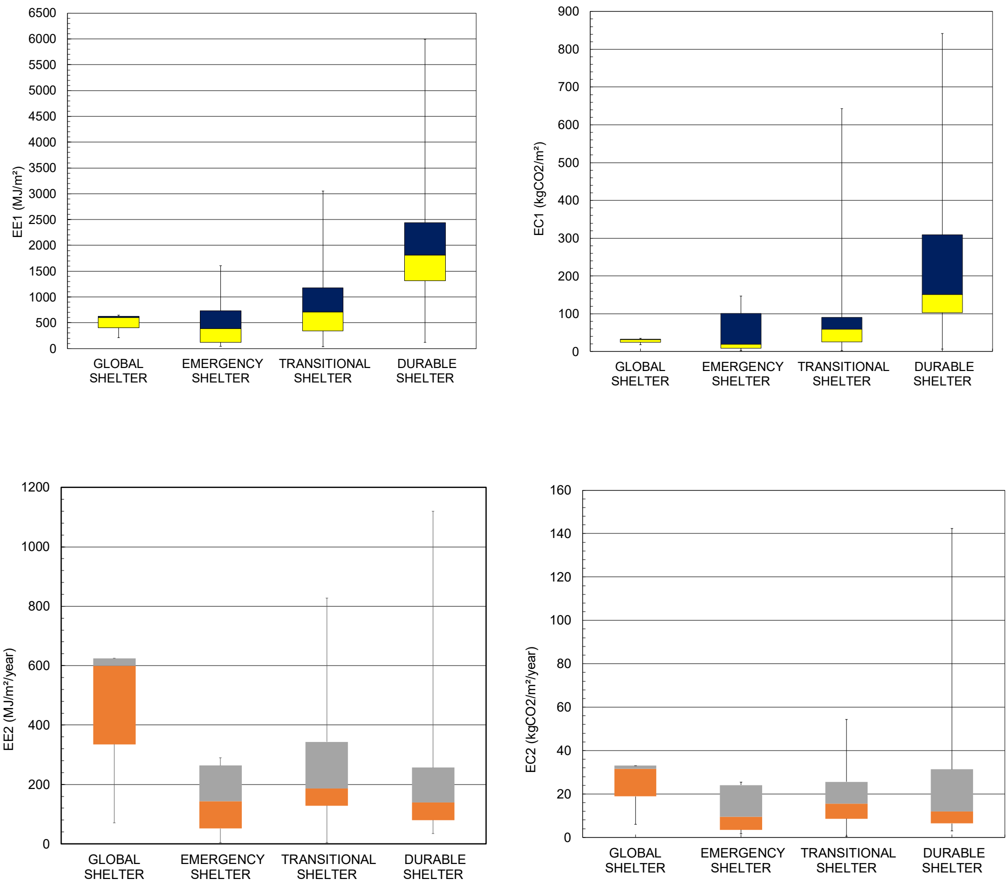


Figure 11: Quartiles for $EE_1$ and $EC_1$ (upper graphs), $EE_2$ and $EC_2$ (lower graphs). These quartiles provide a measure against which designers of shelters can evaluate their designs relative to other shelters.
*Source: Matard 2019*

## Conclusions

This paper presents an analysis of the embodied energy and embodied carbon of eighty-one shelters using data collected in thirty-four countries with the aim of informing early-stage design thinking. The analysis was completed with and without consideration of the service life of the shelters. Importantly, the results are found to not be normally distributed, with most shelters having low embodied energy per $m^2$ ($EE_1$) compared to the maximum found. This is in part due to the wide range of shelters deployed around the world, including Durable shelters, which use more energy intensive materials. It was found that the median $EE_1$ of shelters is approximately 920 MJ/$m^2$ of building footprint, with a 95 percent confidence interval of 599 to 1200 MJ/$m^2$. Meanwhile, the median embodied carbon per $m^2$ ($EC_1$) was 90 $kgCO_2e/m^2$, 95 percent CI [39.2, 99.6]. The median embodied energy per m2 per year ($EE_2$) was 155 MJ/$m_2$yr, with 95 percent CI [135, 204] and the median EC2 was 12.9 $kgCO_2e/m^2$yr, 95 percent CI [9.95, 18.9]. To put these numbers in perspective, Iddon and Firth (2013) suggest an $EC_1$ of 456 $kgCO_2e/m^2$ and an EC2 of 7.6 $kgCO_2e/m^2$yr for a new UK detached dwelling with an assumed lifespan of sixty years. For both EE and EC, the median values and quartiles for all four shelter types (Global, Emergency, Transitional, and Durable) become similar if service life is included.

From our results, it is clear that designing for a longer lifetime generally leads to a greater environmental footprint. However, if the results are presented on a per-year of life basis, then this is no longer true. Thus, if durable shelters are used for the full duration of their service lives, they will often have comparable energy and carbon performance to less durable shelters (although this assumes any maintenance of the shelters has only a minor energy and carbon impact).

The embodied energy and carbon of a shelter design tends to be dominated by just a few materials. For 78 percent of shelters in the sample, a single material is responsible for more than half of the shelter's $EE_1$. For 68 percent of shelters, a single material is responsible for more than half the EC per $m^2$ ($EC_1$). Increasing the material efficiency of these materials will, therefore, be important for minimising embodied energy and carbon, wherever practicable.

When aggregated across all eighty-one shelter designs, the three material categories of metal, clay bricks/tiles, and concrete are responsible for 72 percent of total $EE_1$ and 79 percent of total $EC_1$. Timber is also significant in some cases when its biogenic carbon storage benefits are ignored (as in this study due to the cradle-to-gate boundaries). Poly-cotton fabrics were also found to be energy and carbon intensive. They do not prevail in the aggregated figures as they appear in only three of the eighty-one designs considered. However, those designs, called "global shelters," are very commonly deployed in the field and hence poly-cotton may be more important than the summary figures suggest.

The results show a clear benefit of trying to reduce the embodied energy and carbon impact of metals. The coefficients from the ICE Database suggest that increasing the recycled content of metals such as steel and aluminium—the main metals used in shelter construction—can more than halve their EE and EC (Hammond and Jones 2011).

The results would also suggest, in agreement with past studies on the subject (Kuittinen and Winter 2015), that natural materials such as mud, timber, and bamboo have potential for offering sustainable, low impact solutions. While not credited in this study's results due to the cradle-to-gate boundaries, bio-based materials such as timber absorb carbon dioxide during growth and hence might enable low or even net "carbon negative" buildings. However, for such materials to be truly low carbon, they would need to be disposed of appropriately at the end of their service life as the decomposition of bio-based materials put into landfills produces carbon dioxide and methane, the latter being a particularly powerful greenhouse gas (Lockie and Berebecki 2014).

Within the context of a growing refugee crisis, and the use of city-sized camps (Kutupalong in Bangladesh has a population of over 900,000 (UNHCR 2018), the environmental impact of materials in shelter design is becoming of greater interest. This work presents for the first time (to the authors' knowledge) a summary statistical analysis of the embodied energy and carbon for shelters across the world, and a tool that will allow others to examine some of the impacts of their new designs.

## Recommendations

There are, however, other impacts from material use than the ones presented in this research, and further work is needed to examine these within the refugee context. Furthermore, this study and the web tool developed as part of the research, provide results with cradle-to-gate boundaries and does not consider the location of the shelter. It would be interesting at a later date to expand our work to include location.

In the meantime, other researchers who might like to expand the results to include transport emissions are encouraged to take the material quantities we have assembled (see data access statement) for the eighty-one shelters, and when they know the camp's location and likely location of source material, use the method presented in Escamilla and Habert (2015b) where the following equation was applied for the distance materials typically travel within the country the shelter is to be built:

In-country transport distance [km] = 76.275 x $\log_e$(area of country [$km^2$])–621.59 when the country's area is greater than 8870 $km^2$ and 72 km when equal to or less than 8870 $km^2$.

Alternatively, the methods given in Escamilla and Habert (2015a) could be used. International transport from the point of origin of materials to the host country can be assumed to be by bulk freighter, again, as in Escamilla and Habert (2015b).

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## Appendix 1: List of Documents used to Provide Material Volumes

Table 4: List of Documents from which the volume shelter materials were extracted (p = provided in source document; E = estimated by visual inspection). Material quantities for each shelter can be found in the data store pointed to in the data statement above.

| Source Document | Country, Year, and Form, or Name of Shelter | Code | Service Life | How service life was obtained? |
|---|---|---|---|---|
| **1.** Danish Refugee council**:** 1 case study-detailed bill of quantities | Full bamboo, a National Danish Council design, global | T.1 | 4 | P |
| **2.** Shelter Cluster 10 Design**:** 8 case studies-detailed bill of quantities (Joseph et al. 2013) | B.10 Sri Lanka–2007–'Core Shelter' | D.1 | 12 | P |
| | B.8 Bangladesh–2007–'Core-Shelter' | D.2 | 4 | P |
| | Haiti–2010–'T-Shelter' B4 | D.3 | 7.5 | P |
| | Haiti–2010–'T-Shelter' B5 | D.4 | 5 | P |
| | Plastic and timber emergency shelter | E.1 | 2 | P |
| | Haiti–2010–'T-Shelter' | T.2 | 4 | P |
| | Philippines–2011–'Transitional-Shelter' B6 | T.3 | 5 | P |
| | Philippines–2011–'Transitional-Shelter' B7 | T.4 | 5 | P |
| **3.** Shelter Cluster 8 Design**:** 8 case studies—detailed bill of quantities (Joseph et al. 2012) | B.3 Pakistan (2010) - Timber frame | T.5 | 1 | P |
| | B.5 Peru (2007) - Bamboo mat shelter | T.6 | 1 | P |
| | B.6 Haiti (2010) - Steel Frame | T.7 | 1 | P |
| | B.7 Indonesia, Aceh (2005) - Steel frame | T.8 | 5 | P |
| | B.8 Vietnam (2004) - Steel frame | T.9 | 5 | P |
| | Indonesia West Java bamboo frame Shelter | T.10 | 3 | P |
| | Indonesia, Sumatra, Padang (2009) –Timber frame | T.11 | 1 | P |
| | Peru (2007) - Timber frame | T.12 | 2 | P |

| Source Document | Country, Year, and Form, or Name of Shelter | Code | Service Life | How service life was obtained? |
|---|---|---|---|---|
| **4.** Shelter project 2015-2016**:** 15 case studies—partial bill of quantities (Global Shelter Cluster 2017) | Gaza L-shape wood shelter | D.5 | 10 | E |
| | Somalia concrete shelter | D.6 | 10 | E |
| | Vernacular flood-resistant mud and thatch shelter | D.7 | 5 | E |
| | Vernacular Vanuatu palm straw shelter | D.8 | 2 | P |
| | South Sudan Tarpaulin timber communal shelter | E.2 | 2 | P |
| | Fiji metal braced shelter | T.13 | 3 | P |
| | Nepal Metal and bamboo seismic design | T.14 | 2 | P |
| | Nepal Metal and brick seismic design | T.15 | 3 | P |
| | Nigeria reinforced canvas shelter | T.16 | 2 | P |
| | Post-Typhoon Wood hut | T.17 | 2 | P |
| | Rakhine metal shelter | T.18 | 2 | P |
| | Rakhine Timber rush matting shelter | T.19 | 2 | P |
| | T elevated bamboo shelter | T.20 | 3 | P |
| | Tukul shelter Ethiopia project | T.21 | 3 | P |
| | Two-room clay brick shelter | T.22 | 6.5 | E |
| **5.** UNHCR Shelter design catalogue**:** 19 case studies—detailed bill of quantities | L-shape shelter | D.9 | 10 | E |
| | One room shelter (Pakistan) | D.10 | 10 | E |
| | Tent Shelter | E.3 | 2 | P |
| | Tuareg Shelter (option 1) | E.4 | 2 | P |
| | Tuareg Shelter (option 2) | E.5 | 2 | P |
| | Tuareg Tent | E.6 | 2 | P |
| | Tukul shelter (option 1) | E.7 | 3 | P |
| | Tukul shelter (option 2) | E.8 | 3 | P |
| | Wooden gable frame shelter (option 1) | E.9 | 1 | P |
| | Wooden gable frame shelter (option 2) | E.10 | 1.5 | P |
| | Wooden gable frame shelter (option 3) | E.11 | 2 | P |

| Source Document | Country, Year, and Form, or Name of Shelter | Code | Service Life | How service life was obtained? |
|---|---|---|---|---|
| **5.** UNHCR Shelter design catalogue**:** 19 case studies—detailed bill of quantities | Wooden gable frame shelter (option 4) | E.12 | 2.5 | P |
| | Wooden gable frame shelter (option 5) | E.13 | 4 | P |
| | UNHCR family tent | G.1 | 1 | P |
| | UNHCR framed tent | G.2 | 1 | P |
| | UNHCR refugee unit | G.3 | 3 | P |
| | Azraq T-Shelter | T.23 | 3 | P |
| | Compact bamboo shelter | T.24 | 3 | P |
| | Twin elevated shelter | T.25 | 3 | P |
| | Self-build Permanent shelters in Afghanistan | D.24 | 20 | E |
| | Self-build Permanent shelters with stone wall in Afghanistan | D.25 | 20 | E |
| **6.** Shelter Projects 2011-2012 : 20 case studies (Global Shelter Cluster 2013) | Clay brick wall, flat roof shelter | D.14 | 15 | E |
| | Concrete blocks permanent shelters | D.15 | 20 | E |
| | Shed roof compressed mud block shelter | D.16 | 15 | E |
| | Durable shelters with concrete block foundation in Côte d'Ivoire | D.10-2 | 10 | E |
| | Standard UNHCR family tents | E.14 | 3 | P |
| | Gambrel roof type shelter with mud-straw plaster | T.27 | 5 | E |
| | Cocoa lumber transitional shelter | T.33-2 | 8 | E |
| | Durable shelters with concrete block foundation | D.11 | 10 | E |
| | Stone masonry shelter | D.12 | 15 | E |
| | Timber and wooden planks shelter | D.13 | 15 | E |
| | Shed roof compressed mud block shelter | D.16 | 15 | E |
| | Côte d'Ivoire self-recovery shelters | E.11-2 | 5 | P |
| | Timber and bamboo frames shelters built with thatched roofs | T.26 | 5 | P |
| | Open gable roof iron sheet shelter | T.28 | 4 | P |
| | Open gable roof wooden shelter | T.29 | 10 | E |

*Source: Matard 2019*

## Appendix 2: EE and EC of All Shelters

Table 5 presents the embodied energy (EE) and embodied carbon (EC) for all shelters studied

Table 5: Lowest to Highest Amount of EC and EE per Square Meter per year Shelter

| Code | $EE_1$ | $EC_1$ | $EE_2$ | $EC_2$ | Code | $EE_1$ | $EC_1$ | $EE_2$ | $EC_2$ |
|---|---|---|---|---|---|---|---|---|---|
| **T.1** | 36.0 | 2.1 | 12 | 1 | **T.33** | 1162.2 | 87.0 | 145.3 | 10.9 |
| **E.2** | 46.0 | 2.4 | 30.6 | 1.6 | **T.25** | 1161.2 | 88.3 | 387.1 | 29.4 |
| **E.5** | 71.7 | 4.7 | 35.8 | 2.4 | **T.34** | 1205.5 | 89.7 | 150.7 | 11.2 |
| **E.4** | 90.1 | 5.3 | 45.1 | 2.6 | **T.33-2** | 1221.3 | 89.7 | 152.7 | 11.2 |
| **T.24** | 72.5 | 5.9 | 24.2 | 2.0 | **T.30** | 1120.7 | 90.7 | 140.1 | 11.3 |
| **D.8** | 119.1 | 7.2 | 59.5 | 3.6 | **T.7** | 1200 | 91.4 | 1200 | 91.4 |
| **E.14** | 153.0 | 8.2 | 51.0 | 2.7 | **E.16** | 920 | 95.7 | 230.7 | 23.9 |
| **E.15** | 105.0 | 8.3 | 52.5 | 4.1 | **T.28** | 1405.1 | 97.5 | 351.3 | 24.4 |
| **E.7** | 112.5 | 8.7 | 37.5 | 2.9 | **D.18** | 1083.3 | 99.6 | 72.2 | 6.6 |
| **E.3** | 123.2 | 13.5 | 61.6 | 6.8 | **T.16** | 489.5 | 101.8 | 244.8 | 50.9 |
| **T.21** | 208.2 | 14.0 | 69.4 | 4.7 | **D.24** | 1496.9 | 102.0 | 74.8 | 5.1 |
| **T.14** | 239.3 | 14.3 | 119.7 | 7.2 | **D.17** | 1327.3 | 103.4 | 88.5 | 6.9 |
| **E.10** | 222.5 | 14.4 | 150 | 9.6 | **D.25** | 1496.9 | 103.5 | 74.8 | 5.2 |
| **T.6** | 184.3 | 15.2 | 184.3 | 15.2 | **E.11** | 1329.8 | 105.6 | 664.9 | 52.8 |
| **D.7** | 254.4 | 15.3 | 50.9 | 3.1 | **E.12** | 1494.1 | 114.4 | 597.6 | 45.7 |
| **E.9** | 255.0 | 15.5 | 255.0 | 15.5 | **D.5** | 1816.3 | 116.9 | 181.6 | 11.7 |
| **T.29** | 287.6 | 16.3 | 28.8 | 1.6 | **T.15** | 1347.5 | 119.0 | 449.2 | 39.7 |
| **T.12** | 208.7 | 18.0 | 103.5 | 9.0 | **E.13** | 1603.6 | 120.2 | 400.9 | 30.1 |
| **T.11** | 283.8 | 18.2 | 283.8 | 18.2 | **E.10-1** | 1363.0 | 121.5 | 272.6 | 24.3 |
| **G.3** | 210.6 | 18.3 | 70.2 | 6.1 | **D.19** | 1915.1 | 138.1 | 130 | 9.2 |
| **E.6** | 407.1 | 19.3 | 203.6 | 9.7 | **T.22** | 1731.1 | 139.9 | 266.3 | 21.5 |
| **E.8** | 390.1 | 23.8 | 130.0 | 7.9 | **D.11** | 1854.3 | 146.1 | 185.4 | 14.6 |
| **E.11-2** | 433.5 | 24.5 | 86.7 | 4.9 | **E.17** | 428.4 | 146.7 | 142.8 | 48.9 |
| **T.35** | 417.9 | 27.5 | 52.2 | 3.4 | **D.12** | 2256.0 | 149.3 | 150.4 | 10.0 |

| Code | $EE_1$ | $EC_1$ | $EE_2$ | $EC_2$ | Code | $EE_1$ | $EC_1$ | $EE_2$ | $EC_2$ |
|---|---|---|---|---|---|---|---|---|---|
| **T.10** | 363.3 | 29.6 | 145.3 | 11.8 | **D.1** | 1461.1 | 152.1 | 121.8 | 12.7 |
| **G.2** | 599.3 | 31.6 | 599.3 | 31.6 | **D.15** | 1894.2 | 188.9 | 94.7 | 9.4 |
| **G.1** | 649.8 | 34.5 | 649.8 | 34.5 | **D.16** | 2441.4 | 193.8 | 162.8 | 15 |
| **T.26** | 655.6 | 36.6 | 131.1 | 7.3 | **D.2** | 2619.5 | 199.3 | 748.4 | 56.9 |
| **T.20** | 406.2 | 37.1 | 135.4 | 12.4 | **T.23** | 1908.2 | 210.2 | 636.1 | 70.1 |
| **T.3** | 454.3 | 37.4 | 90.9 | 7.5 | **T.31** | 2825.9 | 220.5 | 471.0 | 36.7 |
| **T.18** | 629.9 | 39.1 | 314.9 | 19.5 | **T.17** | 921.4 | 273.1 | 458.1 | 140 |
| **T.5** | 425.3 | 39.2 | 425.3 | 39.2 | **D.3** | 2435.2 | 297.3 | 324.7 | 39.6 |
| **E.1** | 549.2 | 41.5 | 274.6 | 20.8 | **D.23** | 2991.3 | 308.9 | 299.1 | 30.9 |
| **T.19** | 681.0 | 42.0 | 340.5 | 21.0 | **D.9** | 2430.2 | 311.9 | 243.0 | 31.2 |
| **T.13** | 821.3 | 48.6 | 273.8 | 16.2 | **D.10-2** | 1272.3 | 320.4 | 127.2 | 32.0 |
| **T.8** | 939.6 | 69.0 | 187.9 | 13.8 | **D.14** | 5119.5 | 453.6 | 341.3 | 30.2 |
| **T.2** | 744.4 | 75.7 | 186.1 | 18.9 | **D.10** | 6000 | 459.4 | 599.3 | 45.9 |
| **T.27** | 976.6 | 78.7 | 195.3 | 15.7 | **D.4** | 3147.6 | 528.1 | 699.5 | 120.4 |
| **D.22** | 693.9 | 80.9 | 34.7 | 4.0 | **T.4** | 3050.1 | 642.6 | 610.0 | 128.5 |
| **T.9** | 1022.1 | 85.2 | 204.4 | 17.0 | **D.6** | 1548.8 | 840 | 155 | 84.1 |
| **D.13** | 1226.5 | 90 | 81.8 | 5.8 | | | | | |

*Source: Matard 2019*

## Appendix 3: The EE/EC Web Tool

The calculator was scripted in three parts: An HTML document defining the objects and structure of the website interface, a JavaScript document containing the program logic and performing the calculations, and a CSS document defining the layout of the web page, the link to the website (web-tool) is: https://www.hhftd.net/calculator.

Instructions on how to use the web-based tool using the example shelter in Table 6 are provided on the website.

Table 6: Example of Data Needed to Input a Shelter into the Tool

| **Service life** | 2 years | **Footprint** | 4.86 m² |
|---|---|---|---|
| **Item** | | **Weight** | |
| *Portland Cement* | | 85.0 kg | |
| *Aggregates* | | 1792.0 kg | |
| *Sand* | | 1344.0 kg | |
| *70mm x 40mm x 2.7m Long Softwood Poles* | | 107.95 kg | |
| *80mm x 80mm x 2.7m Long Softwood Poles* | | 26.44 kg | |
| *Plastic Tarpaulin ( HDPE )* | | 19.44 kg | |
| *Steel Wire* | | 0.008270 kg | |
| *75mm Long Steel Nails* | | 1.5 kg | |
| *32 mm Long Steel Nails* | | 1.5 kg | |

*Source: Matard 2019*

The tool was tested on volunteers at the University of Bath to ensure all instructions were clear and appropriate. Due to time constraints, a sample of only 11 students was gathered. Input consistency was studied by asking the 11 to analyse a pre-defined shelter. The expected results of the exercise were $EE_2$ = 270MJ/m²/yr and $EC_2$ = 20 kg$CO_{2e}$/m²/yr. The results collected from the 11 surveyed users established that the standard deviation of output to the actual result was 8 MJ/m²/yr (i.e. within 3 percent of the expected result) for $EE_2$ and 2 kg$CO_2$e/m²/yr (within 10 percent of the expected result) for $EC_2$. This suggests that the interface and instructions, whilst not perfect, seem effective. The discrepancies were found to arise from users choosing slightly different materials from the drop-down menus, rather than entering incorrect quantities. For example, some users correctly chose “steel bar” as the shelter in question required, whereas others simply opted for “steel.”

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